First Measurement of the b-jet Cross Section in Events with a W Boson in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] B. Álvarez González[t],[12] S. Amerio[z],[44] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[49] B.A. Barnett,[26] P. Barria[bb],[47] P. Bartos,[15] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] D. Beecher,[31] S. Behari,[26] G. Bellettini[aa],[47] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello[z],[44] I. Bizjak[ff],[31] R.E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau[a],[11] A. Bridgeman,[25] L. Brigliadori[y],[6] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[50] S. Budd,[25] S. Burke,[18] K. Burkett,[18] G. Busetto[z],[44] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera[v],[17] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli[14],[18] A. Canepa,[46] B. Carls,[25] D. Carlsmith,[60] R. Carosi,[47] S. Carrillo[n],[19] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro[y],[6] P. Catastini[bb],[47] D. Cauz[ee],[55] V. Cavaliere[bb],[47] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito[p],[31] S.H. Chang,[62] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[62] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] S.H. Chuang,[53] K. Chung[o],[18] W.H. Chung,[60] Y.S. Chung,[50] T. Chwalek,[27] C.I. Ciobanu,[45] M.A. Ciocci[bb],[47] A. Clark,[21] D. Clark,[7] G. Compostella,[44] M.E. Convery,[18] J. Conway,[8] M. Cordelli,[20] G. Cortiana[z],[44] C.A. Cox,[8] D.J. Cox,[8] F. Crescioli[aa],[47] C. Cuenca Almenar[v],[8] J. Cuevas[t],[12] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso[aa],[47] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6] P.F. Derwent,[18] A. Di Canto[aa],[47] G.P. di Giovanni,[45] C. Dionisi[dd],[52] B. Di Ruzza[ee],[55] J.R. Dittmann,[5] M. D'Onofrio,[4] S. Donati[aa],[47] P. Dong,[9] J. Donini,[44] T. Dorigo,[44] S. Dube,[53] J. Efron,[40] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H.C. Fang,[29] S. Farrington,[43] W.T. Fedorko,[14] R.G. Feild,[61] M. Feindt,[27] J.P. Fernandez,[32] C. Ferrazza[cc],[47] R. Field,[19] G. Flanagan,[49] R. Forrest,[8] M.J. Frank,[5] M. Franklin,[23] J.C. Freeman,[18] I. Furic,[19] M. Gallinaro,[52] J. Galyardt,[13] F. Garberson,[11] J.E. Garcia,[21] A.F. Garfinkel,[49] P. Garosi[bb],[47] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu[dd],[52] V. Giakoumopoulou,[3] P. Giannetti,[47] K. Gibson,[48] J.L. Gimmell,[50] C.M. Ginsburg,[18] N. Giokaris,[3] M. Giordani[ee],[55] P. Giromini,[20] M. Giunta,[47] G. Giurgiu,[26] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[38] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[33] O. González,[32] I. Gorelov,[38] A.T. Goshaw,[17] K. Goulianos,[51] A. Gresele[z],[44] S. Grinstein,[23] C. Grosso-Pilcher,[14] R.C. Group,[18] U. Grundler,[25] J. Guimaraes da Costa,[23] Z. Gunay-Unalan,[36] C. Haber,[29] K. Hahn,[33] S.R. Hahn,[18] E. Halkiadakis,[53] B.-Y. Han,[50] J.Y. Han,[50] F. Happacher,[20] K. Hara,[56] D. Hare,[53] M. Hare,[57] S. Harper,[43] R.F. Harr,[59] R.M. Harris,[18] M. Hartz,[48] K. Hatakeyama,[51] C. Hays,[43] M. Heck,[27] A. Heijboer,[46] J. Heinrich,[46] C. Henderson,[33] M. Herndon,[60] J. Heuser,[27] S. Hewamanage,[5] D. Hidas,[17] C.S. Hill[c],[11] D. Hirschbuehl,[27] A. Hocker,[18] S. Hou,[1] M. Houlden,[30] S.-C. Hsu,[29] B.T. Huffman,[43] R.E. Hughes,[40] U. Husemann,[61] M. Hussein,[36] J. Huston,[36] J. Incandela,[11] G. Introzzi,[47] M. Iori[dd],[52] A. Ivanov,[8] E. James,[18] D. Jang,[13] B. Jayatilaka,[17] E.J. Jeon,[62] M.K. Jha,[6] S. Jindariani,[18] W. Johnson,[8] M. Jones,[49] K.K. Joo,[62] S.Y. Jun,[13] J.E. Jung,[62] T.R. Junk,[18] T. Kamon,[54] D. Kar,[19] P.E. Karchin,[59] Y. Kato[m],[42] R. Kephart,[18] W. Ketchum,[14] J. Keung,[46] V. Khotilovich,[54] B. Kilminster,[18] D.H. Kim,[62] H.S. Kim,[62] H.W. Kim,[62] J.E. Kim,[62] M.J. Kim,[20] S.B. Kim,[62] S.H. Kim,[56] Y.K. Kim,[14] N. Kimura,[56] L. Kirsch,[7] S. Klimenko,[19] B. Knuteson,[33] B.R. Ko,[17] K. Kondo,[58] D.J. Kong,[62] J. Konigsberg,[19] A. Korytov,[19] A.V. Kotwal,[17] M. Kreps,[27] J. Kroll,[46] D. Krop,[14] N. Krumnack,[5] M. Kruse,[17] V. Krutelyov,[11] T. Kubo,[56] T. Kuhr,[27] N.P. Kulkarni,[59] M. Kurata,[56] S. Kwang,[14] A.T. Laasanen,[49] S. Lami,[47] S. Lammel,[18] M. Lancaster,[31] R.L. Lander,[8] K. Lannon[s],[40] A. Lath,[53] G. Latino[bb],[47] I. Lazzizzera[z],[44] T. LeCompte,[2] E. Lee,[54] H.S. Lee,[14] S.W. Lee[u],[54] S. Leone,[47] J.D. Lewis,[18] C.-S. Lin,[29] J. Linacre,[43] M. Lindgren,[18] E. Lipeles,[46] A. Lister,[8] D.O. Litvintsev,[18] C. Liu,[48] T. Liu,[18] N.S. Lockyer,[46] A. Loginov,[61] M. Loreti[z],[44] L. Lovas,[15] D. Lucchesi[z],[44] C. Luci[dd],[52] J. Lueck,[27] P. Lujan,[29] P. Lukens,[18] G. Lungu,[51] L. Lyons,[43] J. Lys,[29] R. Lysak,[15] D. MacQueen,[34] R. Madrak,[18] K. Maeshima,[18] K. Makhoul,[33] T. Maki,[24] P. Maksimovic,[26] S. Malde,[43] S. Malik,[31] G. Manca[e],[30] A. Manousakis-Katsikakis,[3] F. Margaroli,[49] C. Marino,[27] C.P. Marino,[25] A. Martin,[61] V. Martin[k],[22] M. Martínez,[4] R. Martínez-Ballarín,[32] T. Maruyama,[56] P. Mastrandrea,[52] T. Masubuchi,[56] M. Mathis,[26] M.E. Mattson,[59] P. Mazzanti,[6] K.S. McFarland,[50] P. McIntyre,[54] R. McNulty[j],[30] A. Mehta,[30] P. Mehtala,[24] A. Menzione,[47] P. Merkel,[49] C. Mesropian,[51] T. Miao,[18] N. Miladinovic,[7] R. Miller,[36] C. Mills,[23] M. Milnik,[27] A. Mitra,[1] G. Mitselmakher,[19] H. Miyake,[56] S. Moed,[23]

N. Moggi,[6] M.N. Mondragon[n],[18] C.S. Moon,[62] R. Moore,[18] M.J. Morello,[47] J. Morlock,[27] P. Movilla Fernandez,[18] J. Mülmenstädt,[29] A. Mukherjee,[18] Th. Muller,[27] R. Mumford,[26] P. Murat,[18] M. Mussini[y],[6] J. Nachtman[o],[18] Y. Nagai,[56] A. Nagano,[56] J. Naganoma,[56] K. Nakamura,[56] I. Nakano,[41] A. Napier,[57] V. Necula,[17] J. Nett,[60] C. Neu[w],[46] M.S. Neubauer,[25] S. Neubauer,[27] J. Nielsen[g],[29] L. Nodulman,[2] M. Norman,[10] O. Norniella,[25] E. Nurse,[31] L. Oakes,[43] S.H. Oh,[17] Y.D. Oh,[62] I. Oksuzian,[19] T. Okusawa,[42] R. Orava,[24] K. Osterberg,[24] S. Pagan Griso[z],[44] C. Pagliarone,[55] E. Palencia,[18] V. Papadimitriou,[18] A. Papaikonomou,[27] A.A. Paramonov,[14] B. Parks,[40] S. Pashapour,[34] J. Patrick,[18] G. Pauletta[ee],[55] M. Paulini,[13] C. Paus,[33] T. Peiffer,[27] D.E. Pellett,[8] A. Penzo,[55] T.J. Phillips,[17] G. Piacentino,[47] E. Pianori,[46] L. Pinera,[19] K. Pitts,[25] C. Plager,[9] L. Pondrom,[60] O. Poukhov[*],[16] N. Pounder,[43] F. Prakoshyn,[16] A. Pronko,[18] J. Proudfoot,[2] F. Ptohos[i],[18] E. Pueschel,[13] G. Punzi[aa],[47] J. Pursley,[60] J. Rademacker[c],[43] A. Rahaman,[48] V. Ramakrishnan,[60] N. Ranjan,[49] I. Redondo,[32] P. Renton,[43] M. Renz,[27] M. Rescigno,[52] S. Richter,[27] F. Rimondi[y],[6] L. Ristori,[47] A. Robson,[22] T. Rodrigo,[12] T. Rodriguez,[46] E. Rogers,[25] S. Rolli,[57] R. Roser,[18] M. Rossi,[55] R. Rossin,[11] P. Roy,[34] A. Ruiz,[12] J. Russ,[13] V. Rusu,[18] B. Rutherford,[18] H. Saarikko,[24] A. Safonov,[54] W.K. Sakumoto,[50] O. Saltó,[4] L. Santi[ee],[55] S. Sarkar[dd],[52] L. Sartori,[47] K. Sato,[18] A. Savoy-Navarro,[45] P. Schlabach,[18] A. Schmidt,[27] E.E. Schmidt,[18] M.A. Schmidt,[14] M.P. Schmidt[*],[61] M. Schmitt,[39] T. Schwarz,[8] L. Scodellaro,[12] A. Scribano[bb],[47] F. Scuri,[47] A. Sedov,[49] S. Seidel,[38] Y. Seiya,[42] A. Semenov,[16] L. Sexton-Kennedy,[18] F. Sforza[aa],[47] A. Sfyrla,[25] S.Z. Shalhout,[59] T. Shears,[30] P.F. Shepard,[48] M. Shimojima[r],[56] S. Shiraishi,[14] M. Shochet,[14] Y. Shon,[60] I. Shreyber,[37] A. Simonenko,[16] P. Sinervo,[34] A. Sisakyan,[16] A.J. Slaughter,[18] J. Slaunwhite,[40] K. Sliwa,[57] J.R. Smith,[8] F.D. Snider,[18] R. Snihur,[34] M. Soderberg,[35] A. Soha,[8] S. Somalwar,[53] V. Sorin,[36] T. Spreitzer,[34] P. Squillacioti[bb],[47] M. Stanitzki,[61] R. St. Denis,[22] B. Stelzer,[34] O. Stelzer-Chilton,[34] D. Stentz,[39] J. Strologas,[38] G.L. Strycker,[35] J.S. Suh,[62] A. Sukhanov,[19] I. Suslov,[16] T. Suzuki,[56] A. Taffard[f],[25] R. Takashima,[41] Y. Takeuchi,[56] R. Tanaka,[41] M. Tecchio,[35] P.K. Teng,[1] K. Terashi,[51] J. Thom[h],[18] A.S. Thompson,[22] G.A. Thompson,[25] E. Thomson,[46] P. Tipton,[61] P. Ttito-Guzmán,[32] S. Tkaczyk,[18] D. Toback,[54] S. Tokar,[15] K. Tollefson,[36] T. Tomura,[56] D. Tonelli,[18] S. Torre,[20] D. Torretta,[18] P. Totaro[ee],[55] S. Tourneur,[45] M. Trovato[cc],[47] S.-Y. Tsai,[1] Y. Tu,[46] N. Turini[bb],[47] F. Ukegawa,[56] S. Vallecorsa,[21] N. van Remortel[b],[24] A. Varganov,[35] E. Vataga[cc],[47] F. Vázquez[n],[19] G. Velev,[18] C. Vellidis,[3] M. Vidal,[32] R. Vidal,[18] I. Vila,[12] R. Vilar,[12] T. Vine,[31] M. Vogel,[38] I. Volobouev[u],[29] G. Volpi[aa],[47] P. Wagner,[46] R.G. Wagner,[2] R.L. Wagner,[18] W. Wagner[x],[27] J. Wagner-Kuhr,[27] T. Wakisaka,[42] R. Wallny,[9] S.M. Wang,[1] A. Warburton,[34] D. Waters,[31] M. Weinberger,[54] J. Weinelt,[27] W.C. Wester III,[18] B. Whitehouse,[57] D. Whiteson[f],[46] A.B. Wicklund,[2] E. Wicklund,[18] S. Wilbur,[14] G. Williams,[34] H.H. Williams,[46] P. Wilson,[18] B.L. Winer,[40] P. Wittich[h],[18] S. Wolbers,[18] C. Wolfe,[14] T. Wright,[35] X. Wu,[21] F. Würthwein,[10] A. Yagil,[10] K. Yamamoto,[42] J. Yamaoka,[17] U.K. Yang[q],[14] Y.C. Yang,[62] W.M. Yao,[29] G.P. Yeh,[18] K. Yi[o],[18] J. Yoh,[18] K. Yorita,[58] T. Yoshida[l],[42] G.B. Yu,[50] I. Yu,[62] S.S. Yu,[18] J.C. Yun,[18] L. Zanello[dd],[52] A. Zanetti,[55] X. Zhang,[25] Y. Zheng[d],[9] and S. Zucchelli[y],[6]

(CDF Collaboration[†])

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*University of Athens, 157 71 Athens, Greece*
[4]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798*
[6]*Istituto Nazionale di Fisica Nucleare Bologna, [y]University of Bologna, I-40127 Bologna, Italy*
[7]*Brandeis University, Waltham, Massachusetts 02254*
[8]*University of California, Davis, Davis, California 95616*
[9]*University of California, Los Angeles, Los Angeles, California 90024*
[10]*University of California, San Diego, La Jolla, California 92093*
[11]*University of California, Santa Barbara, Santa Barbara, California 93106*
[12]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[13]*Carnegie Mellon University, Pittsburgh, PA 15213*
[14]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[15]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[16]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[17]*Duke University, Durham, North Carolina 27708*
[18]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[19]*University of Florida, Gainesville, Florida 32611*
[20]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[21]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[22]*Glasgow University, Glasgow G12 8QQ, United Kingdom*

[23]Harvard University, Cambridge, Massachusetts 02138

[24]Division of High Energy Physics, Department of Physics,
University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland

[25]University of Illinois, Urbana, Illinois 61801

[26]The Johns Hopkins University, Baltimore, Maryland 21218

[27]Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany

[28]Center for High Energy Physics: Kyungpook National University,
Daegu 702-701, Korea; Seoul National University, Seoul 151-742,
Korea; Sungkyunkwan University, Suwon 440-746,
Korea; Korea Institute of Science and Technology Information,
Daejeon, 305-806, Korea; Chonnam National University, Gwangju,
500-757, Korea; Chonbuk National University, Jeonju 561-756, Korea

[29]Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720

[30]University of Liverpool, Liverpool L69 7ZE, United Kingdom

[31]University College London, London WC1E 6BT, United Kingdom

[32]Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain

[33]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

[34]Institute of Particle Physics: McGill University, Montréal, Québec,
Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia,
Canada V5A 1S6; University of Toronto, Toronto, Ontario,
Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3

[35]University of Michigan, Ann Arbor, Michigan 48109

[36]Michigan State University, East Lansing, Michigan 48824

[37]Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia

[38]University of New Mexico, Albuquerque, New Mexico 87131

[39]Northwestern University, Evanston, Illinois 60208

[40]The Ohio State University, Columbus, Ohio 43210

[41]Okayama University, Okayama 700-8530, Japan

[42]Osaka City University, Osaka 588, Japan

[43]University of Oxford, Oxford OX1 3RH, United Kingdom

[44]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, [z]University of Padova, I-35131 Padova, Italy

[45]LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France

[46]University of Pennsylvania, Philadelphia, Pennsylvania 19104

[47]Istituto Nazionale di Fisica Nucleare Pisa, [aa]University of Pisa,
[bb]University of Siena and [cc]Scuola Normale Superiore, I-56127 Pisa, Italy

[48]University of Pittsburgh, Pittsburgh, Pennsylvania 15260

[49]Purdue University, West Lafayette, Indiana 47907

[50]University of Rochester, Rochester, New York 14627

[51]The Rockefeller University, New York, New York 10021

[52]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,
[dd]Sapienza Università di Roma, I-00185 Roma, Italy

[53]Rutgers University, Piscataway, New Jersey 08855

[54]Texas A&M University, College Station, Texas 77843

[55]Istituto Nazionale di Fisica Nucleare Trieste/Udine,
I-34100 Trieste, [ee]University of Trieste/Udine, I-33100 Udine, Italy

[56]University of Tsukuba, Tsukuba, Ibaraki 305, Japan

[57]Tufts University, Medford, Massachusetts 02155

[58]Waseda University, Tokyo 169, Japan

[59]Wayne State University, Detroit, Michigan 48201

[60]University of Wisconsin, Madison, Wisconsin 53706

[61]Yale University, New Haven, Connecticut 06520

[62]Center for High Energy Physics: Kyungpook National University,
Daegu 702-701, Korea; Seoul National University, Seoul 151-742,
Korea; Sungkyunkwan University, Suwon 440-746,
Korea; Korea Institute of Science and Technology Information, Daejeon,
305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea

The cross section for jets from b quarks produced with a W boson has been measured in $p\bar{p}$ collision data from 1.9 fb^{-1} of integrated luminosity recorded by the CDF II detector at the Tevatron. The $W + b$-jets process poses a significant background in measurements of top quark production and prominent searches for the Higgs boson. We measure a b-jet cross section of 2.74 ± 0.27(stat.) ± 0.42(syst.) pb in association with a single flavor of leptonic W boson decay over a limited kinematic phase space. This measured result cannot be accommodated in several available theoretical predictions.

The measurement of associated production of a W boson and one or more jets from b quarks, herein referred to as $W + b$-jet production, provides an important test of quantum chromodynamics (QCD). The understanding of this process and its description by current theoretical calculations are important since it is the largest background to the search for the standard model Higgs boson via WH production with decay $H \to b\bar{b}$ [1, 2], to measurements of top quark properties via single [3, 4] and pair production [5–7] with decay $t \to Wb$, and to some searches for physics beyond the standard model [8].

Theoretical predictions for vector boson production with associated b jets have a large uncertainty. Summed fixed-order QCD calculations for $W + b\bar{b} + N$-jets production are available for up to $N=4$ additional light flavor jets and take into account b-quark mass effects [9]. The next-to-leading order (NLO) calculations for $W + b$-jets production in the 1-jet and 2-jet multiplicities show an enhancement over LO up to a factor of two for certain diagrams [10–12]. In order to minimize the impact of the $W + b$-jets theoretical uncertainty in top quark property measurements and searches for WH production, the theoretical prediction for the cross section of $W + b$-jets production is not used in the evaluation of background estimates. Instead, the prediction from theory for the ratio of the event yields from $W + b$ jets and $W +$ inclusive jets, corrected to match what is measured in data control samples, is scaled to the observed cross section of W+jets in data. The systematic uncertainty on the $W + b$-jets yield, driven by imprecise knowledge in the fraction of jets from b production, is approximately 30–

40% [1–7]. These uncertainties are very large compared to the small expected cross sections of the processes mentioned above. We therefore wish to directly measure the $W + b$-jet cross-section with sufficient precision to improve those background estimations. In addition, such a measurement will provide an important constraint on the theoretical predictions. Finally this measurement is a complement to other Tevatron measurements of vector boson plus heavy flavor jet production[13–16].

In this Letter, we describe a measurement of the b-jet cross section in events with a W boson in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV from a data sample corresponding to an integrated luminosity $\mathcal{L}=1.9$ fb^{-1} acquired by the Collider Detector at Fermilab (CDF II)[5]. We select events that are consistent with the electronic or muonic decay of a W boson and contain one or two jets. Among the jets in these selected events, we seek those that originate from b-quark production. Hadrons that contain a b quark have a relatively long lifetime of $\sim$1.6 ps, and a large mass of $\sim$5.3 GeV/c^2 [17]. We exploit the B hadron's long lifetime by examining the charged particles within each jet and attempting to reconstruct a common origin for their trajectories that is well-displaced from the primary $p\bar{p}$ interaction location. The distance between the primary and secondary vertices corresponds to the trajectory through which the relativistically boosted B hadron traveled during its lifetime. The technique is commonly known as vertex b-tagging.

The n_{tag} tagged jets in the selected sample are not purely from b jets. Charm hadrons and certain light flavor hadrons have an appreciable lifetime, and hence jets containing these hadrons can be tagged despite not originating from b-quark production. Also, the finite resolution of the CDF tracking system can allow for spurious displaced vertices. In order to reduce contamination from charm and light flavor/gluon jets, the requirements on the quality of the secondary decay vertex have been optimized for this measurement. Further, we exploit the B hadron's large mass by examining the invariant mass of the charged particles forming the secondary decay vertex (vertex mass, M_{vert}). Vertex mass is correlated with the mass of the parent hadron and partially discriminates between the possible jet flavors to yield the b-jet fraction, f^b. The number of b jets from other processes, $n_{\text{bkg}}^{b\text{ jets}}$, is estimated for top quark pair, single top quark, diboson, and multijet production. The acceptance $\mathcal{A}_{W+b}^{b\text{ jets}}$ is defined with respect to the restricted region of phase space defined below. The b-jet identification efficiency, ϵ_{tag}^b, and the event trigger efficiencies, ϵ, are calibrated with data. The cross section for b jets times the branching fraction for one flavor of $W \to \ell\nu$ decay is defined as

————

*Deceased

†With visitors from ^{a}University of Massachusetts Amherst, Amherst, Massachusetts 01003, ^{b}Universiteit Antwerpen, B-2610 Antwerp, Belgium, ^{c}University of Bristol, Bristol BS8 1TL, United Kingdom, ^{d}Chinese Academy of Sciences, Beijing 100864, China, ^{e}Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, ^{f}University of California Irvine, Irvine, CA 92697, ^{g}University of California Santa Cruz, Santa Cruz, CA 95064, ^{h}Cornell University, Ithaca, NY 14853, ^{i}University of Cyprus, Nicosia CY-1678, Cyprus, ^{j}University College Dublin, Dublin 4, Ireland, ^{k}University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, ^{l}University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017 ^{m}Kinki University, Higashi-Osaka City, Japan 577-8502 ^{n}Universidad Iberoamericana, Mexico D.F., Mexico, ^{o}University of Iowa, Iowa City, IA 52242, ^{p}Queen Mary, University of London, London, E1 4NS, England, ^{q}University of Manchester, Manchester M13 9PL, England, ^{r}Nagasaki Institute of Applied Science, Nagasaki, Japan, ^{s}University of Notre Dame, Notre Dame, IN 46556, ^{t}University de Oviedo, E-33007 Oviedo, Spain, ^{u}Texas Tech University, Lubbock, TX 79609, ^{v}IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain, ^{w}University of Virginia, Charlottesville, VA 22904, ^{x}Bergische Universität Wuppertal, 42097 Wuppertal, Germany, ^{ff}On leave from J. Stefan Institute, Ljubljana, Slovenia,

$$\sigma_{b\text{ jets}} \times \mathcal{B}(W \to \ell\nu) \;=\; \frac{n_{\text{tag}} \cdot f^b - n_{\text{bkg}}^{b\text{ jets}}}{\sum\limits_{i=e,\mu} (\mathcal{L} \cdot \mathcal{A}_{W+b}^{b\text{ jets}} \cdot \epsilon_{\text{tag}}^b \cdot \epsilon)_i} \quad (1)$$

where the sum is over the electron and muon channels.

It is important to note that we quote our result as a jet-level cross section in order to avoid a model-dependent correction on the number of b jets per event that would be required to convert our result into an event-level cross section. Further the result is defined in a restricted region of phase space for the kinematics and multiplicity of the outgoing particles in order to make comparisons with theoretical predictions that minimize extrapolation outside the experimentally accessible region. We define this restricted region of phase space as coincident with our analysis selection criteria, namely to events that contain one or two hadron-level jets with $E_T > 20$ GeV and $|\eta| < 2.0$, an electron or muon with $p_T > 20$ GeV$/c$ and $|\eta| < 1.1$, and a neutrino with $p_T > 25$ GeV$/c$ [18]. We compute the theoretical predictions with these requirements imposed as well.

The data used in this measurement come from the general purpose CDF II detector [19] operating at Fermilab's Tevatron collider. Detailed descriptions of the various subdetectors new for Run II can be found elsewhere [20–24]. The data are collected with a charged lepton trigger that requires an electron (muon) candidate with $|\eta| < 1.0 \ (1.1)$ and $E_T > 18$ GeV ($p_T > 18$ GeV$/c$). The identified charged lepton and the large missing transverse energy, $\not{E}_T$, from the undetected neutrino provide background suppression compared to hadronic W decays. In offline event selection we require a single reconstructed electron (muon) with $E_T > 20$ GeV ($p_T > 20$ GeV$/c$) that is well-isolated from other activity in the calorimeter, and $\not{E}_T > 25$ GeV. A cone-algorithm-based jet reconstruction with cone size $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ is used; jet reconstruction and calibration are described elsewhere [25]. We require exactly one or two jets with $E_T > 20$ GeV and $|\eta| < 2.0$. Events consistent with cosmic rays, $Z \to \ell^+\ell^-$, photon conversions, and multi-jet QCD production are rejected [26]. In data from 1.9 fb^{-1} of integrated luminosity, there are 175,712 events satisfying the W selection and jet requirements.

The b-tagging criteria have been designed for this measurement to obtain a significantly higher purity for b jets and thus reduce the overall systematic uncertainty from the model of the vertex mass distribution. With respect to the default CDF vertex b-tagging [5], this optimized algorithm reduces the rate for false positives of jets from light quark flavors (u, d, s) and gluons by a factor of 10 and charm by a factor of 4 at the expense of a 50% reduction in efficiency for b jets. To be considered for b-tagging, charged particle tracks within the jet cone are required to have $p_T > 0.5$ GeV$/c$, and impact parameter signifi-

cance $\frac{d_0}{\delta_{d_0}} > 3.5$, where the impact parameter d_0 is the distance of closest approach of the particle track to the location of the primary $p\bar{p}$ interaction in the transverse plane with respect to the beam axis, and δ_{d_0} is its uncertainty. Particles must also have an impact parameter less than 0.15 cm, originate from within 2 cm of the primary $p\bar{p}$ interaction location in the z coordinate [18], and have at least a minimum number of hits from the silicon tracking detectors. These requirements reduce contamination from interactions with detector material, multiple $p\bar{p}$ interactions, and misreconstruction, respectively. A common decay vertex is sought among subsets of these selected particles, and if one is found that contains three or more particles, then the decay length in the transverse plane, L_{2D}, is calculated as the projection along the jet axis of the displacement of the secondary vertex with respect to the primary $p\bar{p}$ interaction location. The vertex is required to have decay length significance $\frac{L_{2D}}{\delta_{L_{2D}}} > 7.5$, and pseudo-$c\tau \equiv \frac{L_{2D} \cdot M_{\text{vert}} \cdot c}{p_{T,\text{vert}}} < 1.0$ cm, where the invariant mass M_{vert} and transverse momentum $p_{T,\text{vert}}$ of the vertex are calculated from the constituent particles. Note that the mass of each particle is set to the charged pion mass. Any vertices consistent with K_S^0 and Λ decay, and nuclear interactions in the detector material are rejected. The sign of the vertex tag is determined by the position of the vertex with respect to the jet direction; those on the same (opposite) hemisphere as the jet direction are called positively (negatively) tagged.

Among the events satisfying our event selection, $n_{\text{tag}} = 943$ jets are found to be positively tagged. The flavor composition of the positively tagged sample is determined through a maximum likelihood fit of the distribution of the vertex mass in the data. Simulated distributions for b and charm jets are formed from standard model processes that are major contributors to the selected event sample. Sources of b jets include $W+b$ jets, which is simulated by the Monte Carlo event generator ALPGEN version 2.1.0 [27] with CTEQ5L parton densities [28] and PYTHIA version 6.325 for hadronization [29]; $t\bar{t}$ and diboson production are simulated with PYTHIA version 6.216, and single top quark production by MADEVENT version 4.2.11 [30]. The yields of tagged jets from these processes are determined from the simulated samples scaled to the latest theoretical cross sections [31–33] with the event selection requirements applied.

We check the simulation model of b jets against an independent data sample from double-tagged dijet events collected with a single $p_T > 9$ GeV$/c$ muon trigger. One jet is required to contain the muon, presumably from semileptonic B hadron decay. The other tagged jet in these events is a sample whose b-jet purity is estimated to be above 99%. This sample is used to validate the model of the b-jet vertex mass; the agreement between simulation and data is shown in Fig. 1. We use the difference between simulation and data to estimate the systematic

uncertainty from the b-jet model.

Vertex tags of jets from charm hadrons are primarily due to $W+c$-jets production, which is simulated with ALPGEN. Positive vertex tags of light flavor jets are modeled with a simulation of inclusive jet production from PYTHIA. We use negatively tagged jets in the data as an alternative model for light flavor. This second light flavor model is used in the vertex mass fit to assess the impact of light flavor model choice on the result.
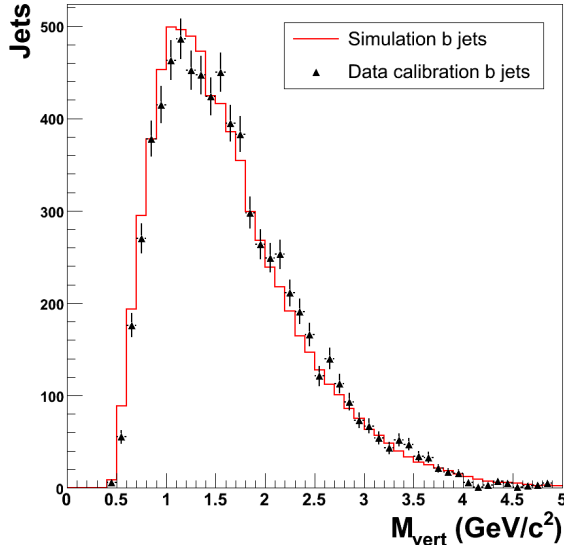

FIG. 1: Comparison of the vertex mass distributions of tagged b jets from a simulated sample and from data.

The maximum likelihood fit of the vertex mass data distribution, shown in Fig. 2, is used to extract two parameters: the fraction of jets from bottom hadrons f^b, and the fraction of jets from charmed hadrons f^c, where the fraction of jets from light flavors is $f^{LF} \equiv 1 - f^b - f^c$. The best fit is $f^b = 0.71 \pm 0.05(\text{stat.})$ corresponding to $670 \pm 44(\text{stat.})$ tagged jets from bottom hadrons. From simulated experiments with flavor compositions similar to the data, we confirmed that our vertex mass fit procedure returns results consistent with the assumed background content. These simulated experiments indicated that the systematic uncertainties on the model of the b, charm, and light flavor vertex mass distributions manifest themselves as relative systematic uncertainties of 0.08, 0.01 and 0.03, respectively, on the fitted b-jet fraction.

This yield of b jets includes our signal but also contains a contribution from other processes with jets from b-quark production. We use simulated samples and the theoretical predictions for production rates of $t\bar{t}$ [31], single top quark [32], and diboson processes (WZ, WW, and ZZ) [33] in order to estimate a contribution of 152 ± 21 b jets from these processes. This includes a small contribution of 7.3 ± 0.8 jets from $W+b$-jets production with $W \to \tau\nu$, which is treated as a background. Sources of
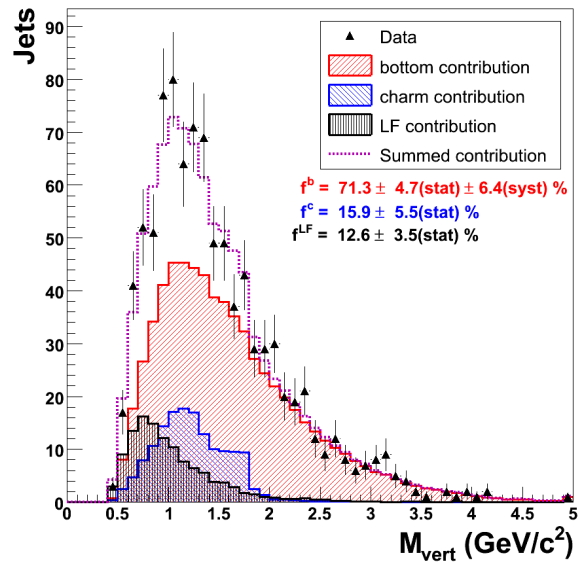

FIG. 2: Maximum likelihood fit of the vertex mass for tagged jets in the selected data sample.

systematic uncertainty in the background yield of tagged b jets include the uncertainty in the b-jet tagging efficiency in the data (a relative 6% uncertainty on all tagged b-jet yields), the uncertainty on the top quark and diboson predicted cross sections (a relative uncertainty of 10% on $t\bar{t}$ and diboson, and 30% on single top yields, which translate to an overall 2% uncertainty on $\sigma_{b\ \text{jets}} \times \mathcal{B}$) and the uncertainty in the accumulated CDF luminosity (a relative 6% on all yields).

We estimate a contribution of 25 ± 8 b-jets from QCD multijet production, where mismeasured jets pass the lepton identification requirements and result in sufficient $\not{E}_T$. As this background is difficult to model with simulation, a complementary data sample was collected with the same high p_T electron trigger, but where the electron candidate failed at least two of the identification criteria [34]. This provides both a model of the $\not{E}_T$ distribution, which is used to estimate the rate of QCD multijet background above our selection [34], and a vertex mass distribution, which is used to determine the fraction of tagged jets from bottom hadrons. The model for tagged jets from multijet production is statistics limited; we recover statistics by relaxing the $\not{E}_T$ requirement and perform the vertex mass distribution fit for $\not{E}_T > 15$ and 20 GeV as well as the default $\not{E}_T > 25$ GeV and use all three results to determine the fitted b fraction from multijet production. The uncertainties on the QCD multijet tagged b-jet background come from the modeling of the $\not{E}_T$ distribution for the overall multijet normalization (a relative 30% uncertainty, which translates to a 1% uncertainty on $\sigma_{b\ \text{jets}} \times \mathcal{B}$), and the spread in the fitted b fraction from vertex mass distribution fits from the different $\not{E}_T$ thresholds (a relative 25% uncertainty, which translates to a 1% uncertainty on $\sigma_{b\ \text{jets}} \times \mathcal{B}$).

After subtracting the background of $n_{\text{bkg}}^{b\text{ jets}} = 177 \pm 22$, we have a yield of $493 \pm 48(\text{stat.})$ tagged b jets from $W+b$ production. We define the acceptance, $\mathcal{A}_{W+b}^{b\text{ jets}}$, of our selection with respect to a restricted region of kinematic phase space, as defined earlier. The phase space restrictions are applied to the outgoing leptonic W daughters and jets in the simulated $W+b$ production ALPGEN events. Hadron-level jets are defined by SPARTY-JET [35] as a collection of simulated final state particles that have been clustered using the same cone algorithm as in the jet reconstruction. A hadron-level jet is said to be b-matched if it has $\Delta R < 0.4$ with respect to a b quark in the simulated event. The matching considers b-quark candidates after showering but before hadronization. The denominator of the acceptance is the number of b-matched hadron-level jets in simulated $W + b$-jet events that pass the phase space requirements as given earlier; the numerator is the number of b-matched reconstructed jets in simulated $W + b$-jet events that pass the phase space requirements and, in addition, the event selection described above through the jet multiplicity requirement. The weighted average acceptance over the electron and muon channels is found to be 0.68 ± 0.03, where the sources that dominate the systematic uncertainty are the jet energy calibration (3%), the factorization and renormalization scale (3%), and the dependence of event kinematics on the parton distribution functions (2%).

For clarity, we separate the b-tag efficiency and several data-based corrections from the acceptance. The b-tag efficiency is the ratio of the number of b-tagged reconstructed b-matched jets to the number of reconstructed b-matched jets in the simulated $W + b$-jet events that have passed the event selection and phase space requirements: $\epsilon_{\text{tag}}^{b,\text{sim}} = 0.177 \pm 0.001(\text{stat.})$. This value needs to be corrected by a factor of $0.88\pm0.01(\text{stat.})\pm0.05(\text{syst.})$, which quantifies the discrepancy in tag efficiency between simulation and data [36]. The corrected b-tag efficiency is then $\epsilon_{\text{tag}}^{b} = 0.156 \pm 0.009$. The final correction factor ϵ is the average over all triggers of the product of the following three terms determined from data: the fraction of events that happen in the luminous region well-contained by the CDF detector, with primary $p\bar{p}$ interaction within 60 cm of the center of the detector along the beam line, 0.963 ± 0.003; the efficiency of the trigger, 0.943 ± 0.004; and the correction factor for charged lepton identification efficiency, 0.969 ± 0.004.

Having obtained all of the information needed as input to Eq. 1, we measure the b-jet cross section to be $\sigma_{b\text{ jets}} \times \mathcal{B}(W \rightarrow \ell\nu) = 2.74 \pm 0.27(\text{stat.}) \pm 0.42(\text{syst.})$ pb with a W boson decaying to a single leptonic flavor within the restricted kinematic phase space defined earlier. The overall relative uncertainty on the measurement is 18%. This uncertainty is dominated by the uncertainty in the b-jet vertex mass model (a relative 8% on $\sigma_{b\text{ jets}} \times \mathcal{B}$), the tag efficiency (6%), and the luminosity (6%). The

results in the electron and muon channels were examined independently as a cross check and are consistent.

Finally, we have determined the theoretical prediction of $\sigma_{b\text{ jets}} \times \mathcal{B}$, using our kinematic definition above, at leading order from PYTHIA and at summed fixed-order from ALPGEN. The PYTHIA prediction is 1.10 pb and the ALPGEN prediction is 0.78 pb, assuming a Q^2 scale of $M_W^2 + p_{\text{T},W}^2$; these predictions are factors of 2.5-3.5 lower than our result. These are important comparisons given the wide use of these programs in the generation of simulated physics events at the Tevatron and LHC experiments. A NLO calculation of $\sigma_{b\text{ jets}} \times \mathcal{B}$ has recently been completed [37]; their prediction of $1.22 \pm 0.14(\text{syst.})$ pb is also low with respect to the measured value. Further study is underway to examine the differential cross section as a function of jet kinematics and compare to LO, summed fixed-order and NLO predictions.

[1] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D **78**, 032008 (2008).

[2] V. M. Abazov et al. (DØ Collaboration), Phys. Rev. Lett. **102**, 051803 (2009).

[3] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. **103**, 092002 (2009).

[4] V. M. Abazov et al. (DØ Collaboration), Phys. Rev. Lett. **103**, 092001 (2009).

[5] D. Acosta et al. (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).

[6] R. Demina and E. Thomson, Annu. Rev. Nucl. Part. Sci. **58**, 125 (2008).

[7] V. M. Abazov et al. (DØ Collaboration), Phys. Rev. D **74**, 112004 (2006).

[8] H. S. Goh, S. Su, Phys. Rev. D **75**, 075010 (2007).

[9] M. L. Mangano et al., Nucl. Phys. B **632**, 343 (2002).

[10] J. Campbell et al., Phys. Rev. D **75**, 054015 (2007).

[11] F. Febres Cordero et al., Phys. Rev. D **74**, 034007 (2006).

[12] J. Campbell et al., Phys. Rev. D **79**, 034023 (2009).

[13] T. Aaltonen et al., Phys. Rev. **D79**, 052008 (2009).

[14] V. M. Abazov et al., Phys. Rev. Lett. **94**, 161801 (2005).

[15] T. Aaltonen et al., Phys. Rev. Lett. **100**, 091803 (2008).

[16] V. M. Abazov et al., Phys. Lett. **B666**, 23 (2008).

[17] C. Amsler et al., Phys. Lett. B **667**, 1 (2008).

[18] We use a cylindrical coordinate system in which the z axis is along the proton beam direction and θ is the polar angle. Pseudorapidity is $\eta = -\ln\tan(\theta/2)$, while transverse momentum is $p_T = |p|\sin\theta$, and transverse energy is $E_T = E\sin\theta$. Missing transverse energy, $\not{E}_T$, is defined as the magnitude of $-\sum_i E_T^i \hat{n}_i$, where $\hat{n}_i$ is the unit vector in the azimuthal plane that points from the beam line to the ith calorimeter tower.

[19] A. Abulencia et al. (CDF Collaboration), J. Phys. G Nucl. Part. Phys. **34** (2007).

[20] A. Sill, Nucl. Instrum. Methods A **447**, 1 (2000).

[21] A. Affolder et al., Nucl. Instrum. Methods A **453**, 84 (2000).

[22] C. S. Hill et al., Nucl. Instrum. Methods A **511**, 118 (2003).

[23] A. Affolder et al., Nucl. Instrum. Methods A **526**, 249 (2004).

[24] D. Acosta et al., Nucl. Instrum. Methods A **494**, 57 (2002).

[25] A. Bhatti et al., Nucl. Instrum. Methods A **566**, 375 (2006).

[26] T. Aaltonen et al (CDF Collaboration), Phys. Rev. Lett. **101**, 252001 (2008).

[27] M. L. Mangano et al., J. High Energy Phys. **0307**, 001 (2003).

[28] H. L. Lai et al. (CTEQ Collaboration), Eur. Phys. J. C **12**, 375 (2000).

[29] T. Sjöstrand et al., Comput. Phys. Commun. **135**, 238 (2001).

[30] J. Alwall et al., Journ. HEP **0709**, 028 (2007).

[31] S. Moch and P. Uwer, Phys. Rev. D **78**, 034003 (2008).

[32] B. W. Harris et al., Phys. Rev. D **66**, 054024 (2002).

[33] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).

[34] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D **77**, 011108 (2008).

[35] S. D. Ellis, J. Huston, K. Hatakeyama, P. Loch and M. Tonnesmann, Prog. Part. Nucl. Phys. **60**, 484 (2008).

[36] C. Neu, PoS TOP2006 p. 015 (2006).

[37] J. Campbell, F. Febres Cordero, L. Reina, private communication (2009).